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ABSTRACT (UNCLASSIFIED)

In this report the transmission equation for a planar near-field measurement configuration is derived for the situation in which the Antenna Under Test is operated as a receiving antenna. (Usually the Antenna Under Test is operated as a transmitting antenna).
This transmission equation has the same form as that derived for the situation in which the Antenna Under Test is acting as transmitting antenna. With this new derived and with the existing transmission equation, it is possible to characterize non-reciprocal antennas, provided that the used probe is completely characterized.

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SAMENVATTING (ONGERUBRICEERD)

In dit rapport wordt de transmissievergelijking voor een planaire nabije-veldmeetopstelling afgeleid voor de situatie waarin de testantenne gebruikt wordt als ontvangstantenne. (Normaal gesproken wordt de testantenne gebruikt als zendantenne).
Deze transmissievergelijking heeft dezelfde vorm als die afgeleid voor de situatie waarin de testantenne als zendantenne werkt. Met deze nieuw afgeleide en met de bestaande transmissievergelijking is het mogelijk niet-reciproke antennes te karakteriseren, mits de gebruikte probe geheel is gekarakteriseerd.

CONTENTS

1 INTRODUCTION

In the FEL-TNO planar near field measurement configuration, the Antenna Under Test (AUT) is operated as a transmitting antenna and the probe as a receiving antenna, see figure 1 [1]:

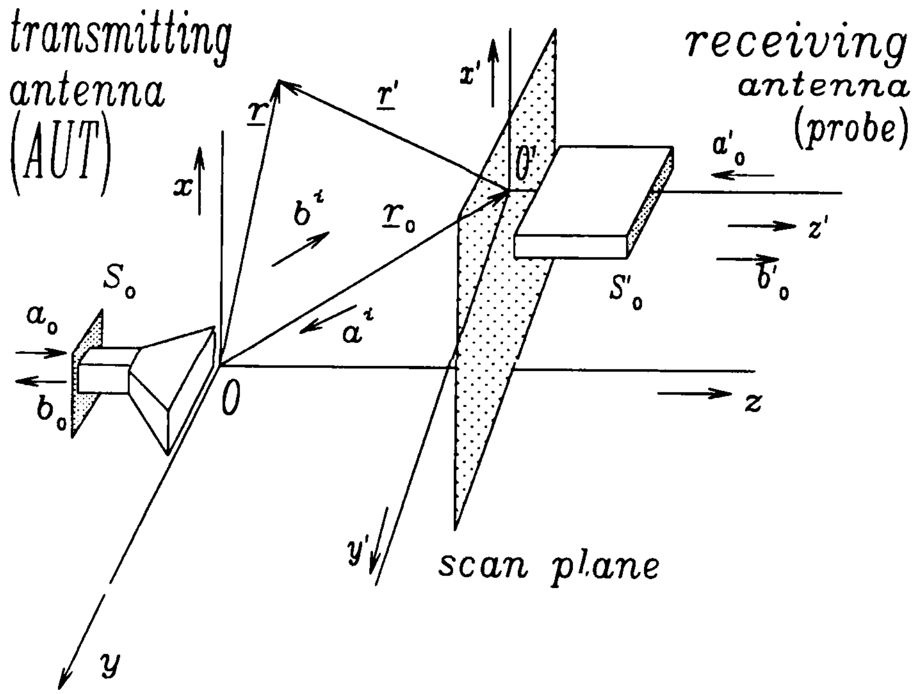

Fig. 1: Planar near-field measurement configuration

a_0 and a_0' are signals supplied to the antennas, b_0 and b_0' are signals received by the antennas. The quantities a^i and b^i are spectrum density functions for incoming and outgoing waves and are defined in [1]. As indicated in the above figure, primes are used to associate symbols with the probe.

The relationship between a_0 and b_0' is given by [1]:

$$b_0'(\underline{r}_0) = \frac{a_0}{1 - \Gamma_0'\Gamma_1'} \, .$$

$$\cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sum_{i=1}^{2} R'^{i}(k_x,k_y) \,.\, T^{i}(k_x,k_y) \,.\, \exp(+j\underline{k}\cdot\underline{r}_0)\, dk_x dk_y \qquad (1)$$

This equation is known as the transmission equation [2].
In the above equation, Γ_0' corresponds to the reflection coefficient at S_0' looking toward the probe and Γ_1' is the reflection coefficient when looking from probe into its load. $R'^{i}(k_x, k_y)$ and $T^{i}(k_x, k_y)$ are associated with respectively the receiving properties of the probe and the transmitting properties of the AUT [1].

When the AUT is an active or non-reciprocal antenna, it will have different characteristics in receive and transmit-mode. Therefore it is necessary that measurements also will be carried out for the situation in which the AUT is operated as a receiving antenna and the probe as a transmitting antenna.
It will be proven that for this situation a similar transmission equation as stated above (1) will hold true.

2 ANTENNA UNDER TEST IN RECEIVE-MODE

The 'new' near-field measurement configuration is shown in figure 2:

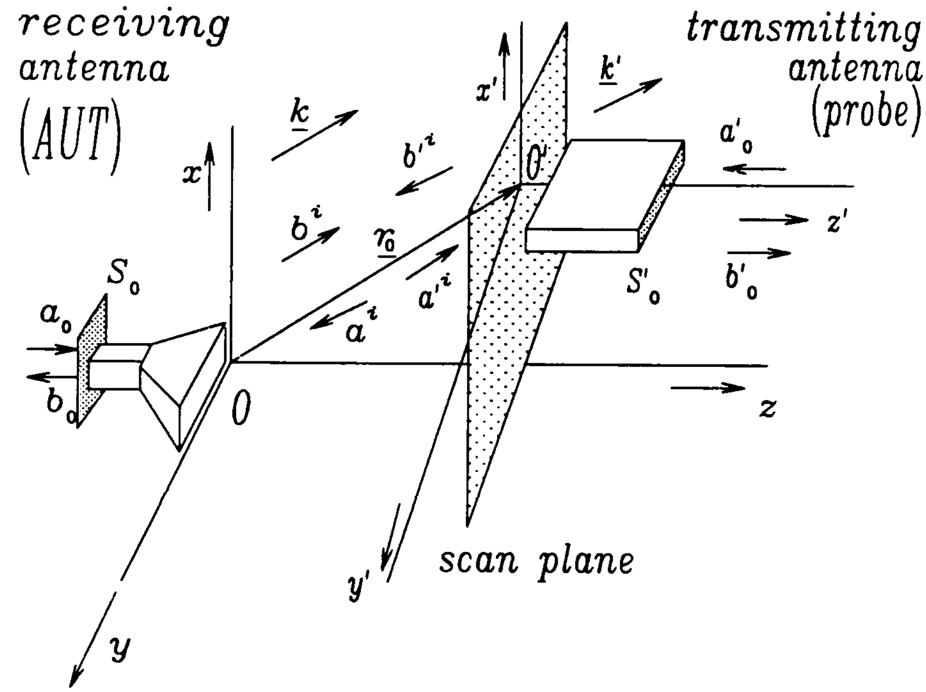

Fig. 2: Planar near-field measurement configuration with AUT in receive-mode

The relationship between a_0' and b_0 is derived in the same way as the relationship between a_0 and b_0'. For the derivation of the latter, the reader is referred to [1]. In the following the derivation of the relationship between a_0' and b_0 will be briefly outlined:

A plane wave, that originates from the x'y'-plane, is given by:

$$\underline{E}' = \underline{A}'(\underline{k}').\exp(+j\underline{k}'\cdot\underline{r}') \qquad (2)$$

The basis fields are now given by:

$$\underline{E}_1'^{\pm}(\underline{k}',\underline{r}') = [\underline{K}_1' \mp K'\gamma'^{-1}\underline{a}_z'].\exp(+j\underline{k}'\cdot\underline{r}') \qquad (3a)$$

$$\underline{H}_1'^{\pm}(\underline{k}',\underline{r}') = \pm\eta_1.\underline{a}_z'\times\underline{K}_1'.\exp(+j\underline{k}'\cdot\underline{r}'); \quad \eta_1 = \omega\epsilon/\gamma' \qquad (3b)$$

and:

$$\underline{E}_2'^{\pm}(\underline{k}',\underline{r}') = \underline{K}_2'.\exp(+j\underline{k}'\cdot\underline{r}') \qquad (3c)$$

$$\underline{H}_2'^{\pm}(\underline{k}',\underline{r}') = [\pm\eta_2.\underline{a}_z'\times\underline{K}_2' + K'(\omega\mu)^{-1}.\underline{a}_z'].\exp(+j\underline{k}'\cdot\underline{r}'); \quad \eta_2 = \gamma'/(\omega\mu) \qquad (3d)$$

In the above equations, in analogy with [1]:

$$\underline{K}_1' = \underline{K}'/K'; \ \underline{K}' = k_x'.\underline{a}_x' + k_y'.\underline{a}_y'; \ K' = |\underline{K}'| \qquad (4a)$$

$$\underline{K}_2' = \underline{a}_z'\times\underline{K}_1' \qquad (4b)$$

$$k_z' = \pm\gamma'; \ \gamma' = (k'^2 - K'^2)^{1/2}; \ k'^2 = \underline{k}'\cdot\underline{k}' \qquad (4c)$$

In (4c) $+\gamma'$ is associated with a plane wave travelling into the positive z'-direction' $-\gamma'$ is associated with a plane wave travelling into the negative z'-direction. The signs in equations (3a,b,c,d) have the same meaning; they indicate the direction of wave propagation.
The field $\underline{E}'(\underline{r}')$ *transmitted* by the probe in the region $z'<0$ for a specified propagation vector $\underline{k}'$, can now be given as a combination of

fields $\underline{E}_1'^-(\underline{k}',\underline{r}')$ and $\underline{E}_2'^-(\underline{k}',\underline{r}')$. So the plane wave spectrum expansion is given by:

$$\underline{E}'(\underline{r}') = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[b'^1(k_x',k_y').\underline{E}_1'^-(\underline{K}',\underline{r}') +$$

$$+ b'^2(k_x',k_y').\underline{E}_2'^-(\underline{K}',\underline{r}')]dk_x'dk_y' \qquad (5)$$

in which the coefficients $b'^1(k_x', k_y')$ and $b'^2(k_x', k_y')$ are referred to as spectrum density functions of outgoing waves.

The relationship between $\underline{r}$ and $\underline{r}'$ is given by [1] (see also figure 1):

$$\underline{r} = \underline{r}_0 + \underline{r}' \quad \Leftrightarrow \quad \underline{r}' = \underline{r} - \underline{r}_0 \qquad (6)$$

and so:

$$\begin{aligned}\underline{E}_1'^-(\underline{K}',\underline{r}') &= [\underline{K}_1' + K'\gamma'^{-1}\underline{a}_z'].\exp(+j\underline{k}'\cdot\underline{r}') = \\ &= [\underline{K}_1' + K'\gamma'^{-1}\underline{a}_z'].\exp(+j\underline{k}'\cdot\underline{r}).\exp(-j\underline{k}'\cdot\underline{r}_0) = \\ &= \underline{E}_1'^-(\underline{K}',\underline{r}).\exp(-j\underline{k}'\cdot\underline{r}_0) \qquad (7)\end{aligned}$$

and in the same way:

$$\underline{E}_2'^-(\underline{K}',\underline{r}') = \underline{E}_2'^-(\underline{K}',\underline{r}).\exp(-j\underline{k}'\cdot\underline{r}_0) \qquad (8)$$

Substitution of equations (7) and (8) in (5) gives for the field incident upon the AUT:

$$\underline{\mathbf{E}}'(\underline{\mathbf{r}}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[b'^{1}(k_x',k_y').e^{-j\underline{\mathbf{k}}'\cdot\underline{\mathbf{r}}_0}.\underline{\mathbf{E}}_1'^{-}(\underline{\mathbf{K}}',\underline{\mathbf{r}}) +$$

$$+ b'^{2}(k_x',k_y').e^{-j\underline{\mathbf{k}}'\cdot\underline{\mathbf{r}}_0}.\underline{\mathbf{E}}_2'^{-}(\underline{\mathbf{K}}',\underline{\mathbf{r}})]dk_x'dk_y' =$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[a^{1}(k_x',k_y').\underline{\mathbf{E}}_1'^{-}(\underline{\mathbf{K}}',\underline{\mathbf{r}}) +$$

$$+ a^{2}(k_x',k_y').\underline{\mathbf{E}}_2'^{-}(\underline{\mathbf{K}}',\underline{\mathbf{r}})]dk_x'dk_y' \qquad (9)$$

where:

$$a^{i}(k_x',k_y') = b'^{i}(k_x',k_y').\exp(-j\underline{\mathbf{k}}'\cdot\underline{\mathbf{r}}_0); \quad i = 1,2 \qquad (10a)$$

are the spectrum density functions of the waves incoming on the AUT. Since $\underline{\mathbf{k}}' = \underline{\mathbf{k}}$ (see figure 2), equation (10a) gives:

$$a^{i}(k_x,k_y) = b'^{i}(k_x,k_y).\exp(-j\underline{\mathbf{k}}\cdot\underline{\mathbf{r}}_0); \quad i = 1,2 \qquad (10b)$$

The scattering equations of an antenna in the x,y-plane are given by [1, 3, 4]:

$$b_0 = \Gamma_0 . a_0 + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sum_{i=1}^{2} R^{i}(k_x,k_y).a^{i}(k_x,k_y)dk_x dk_y \qquad (11a)$$

$$b^i(k_x,k_y) = T^i(k_x,k_y).a_0 + \\ + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sum_{j=1}^{2} S^{i,j}(k_x,k_y;l_x,l_y).a^j(l_x,l_y)dl_x dl_y \tag{11b}$$

Γ_0 corresponds to the reflection coefficient at S_0 looking toward the antenna (figure 1 and 2); $R^i(k_x, k_y)$ and $T^i(k_x, k_y)$ are associated with the receiving and transmitting properties of the antenna, respectively and $S^{i,j}$ describes the scattering properties. Reception from a certain direction (k_x, k_y) depends on the scattering in all directions (l_x, l_y) from an object in front of the antenna.

The double integral in (11b) is omitted, assuming that multiple reflections between AUT and probe do not occur.

Γ_1 is the reflection coefficient, looking from AUT into the load, so:

$$a_0 = \Gamma_1.b_0 \tag{12}$$

Equation (11b), provided with primes for the probe, substituted in (10) gives:

$$a^i(k_x,k_y) = a_0'.T'^i(k_x,k_y).\exp(-j\underline{\mathbf{k}}\cdot\underline{\mathbf{r}}_0) \tag{13}$$

and, finally, (12) and (13) substituted in (11a) leads to:

$$b_0 = \Gamma_0.\Gamma_1.b_0 + a_0'. \\ .\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sum_{i=1}^{2} R^i(k_x,k_y).T'^i(k_x,k_y).e^{-j\underline{\mathbf{k}}\cdot\underline{\mathbf{r}}_0}dk_x dk_y \tag{14a}$$

or:

$$b_0(\underline{0};\underline{r}_0) = \frac{a_0'}{1 - \Gamma_0\Gamma_1} \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sum_{i=1}^{2} R^i(k_x,k_y) \,.\, T'^i(k_x,k_y) \,.\, e^{-j\underline{k}\cdot\underline{r}_0}\, dk_x dk_y \tag{14b}$$

in which $b_0(\underline{0};\underline{r}_0)$ means the output of the AUT in the origin $\underline{0}$ of the coordinate system and for a probe position $\underline{r}_0$.

This equation is, with exception of the position of the primes and the sign of the exponent, identical to the known transmission equation (1). From the above equation the AUT receiving characteristic $R^i(k_x, k_y)$ can be obtained, provided that the probe transmitting characteristic $T'^i(k_x, k_y)$ is known.

3 CALCULATION OF THE RECEIVING FAR-FIELD PATTERN

The active (non-reciprocal) AUT can be considered as existing of two different *reciprocal* antennas; one representing the AUT in receive mode and one representing the AUT in transmit mode.

Suppose now that the AUT in receive mode is a *reciprocal* antenna with receiving characteristic $R^i(k_x, k_y)$; i=1,2. For a reciprocal antenna, the receiving far-field pattern is the same as the transmitting far-field pattern and the transmitting far-field pattern can be calculated:

For a reciprocal antenna, the following equation holds true [5]:

$$\eta_0 . k . \underline{r}(\underline{K}) = \gamma . \eta . \underline{t}(-\underline{K}); \qquad \eta = (\epsilon/\mu)^{1/2} \tag{15}$$

where η_0 is the characteristic admittance of the antenna (in the receiving mode).
The complete transmitting and receiving characteristics $\underline{t}(\underline{K})$ and $\underline{r}(\underline{K})$ are given by [5]:

$$\begin{aligned}\underline{t}(\underline{K}) &= [k/\gamma] . T^1(\underline{K}) . \underline{\mathbf{a}}_{|}(\underline{k}) + T^2(\underline{K}) . \underline{\mathbf{a}}_{\perp}(\underline{k}) = \\ &= [k/\gamma] . T^1(k_x, k_y) . \underline{\mathbf{a}}_{|}(\underline{k}) + T^2(k_x, k_y) . \underline{\mathbf{a}}_{\perp}(\underline{k})\end{aligned} \tag{16a}$$

$$\begin{aligned}\underline{r}(\underline{K}) &= -[\gamma/k] . R^1(\underline{K}) . \underline{\mathbf{a}}_{|}(\underline{k}) + R^2(\underline{K}) . \underline{\mathbf{a}}_{\perp}(\underline{k}) = \\ &= -[\gamma/k] . R^1(k_x, k_y) . \underline{\mathbf{a}}_{|}(\underline{k}) + R^2(k_x, k_y) . \underline{\mathbf{a}}_{\perp}(\underline{k})\end{aligned} \tag{16b}$$

with:

$$\underline{\mathbf{a}}_{\perp}(\underline{k}) = \underline{K}_2 = \underline{\mathbf{a}}_z x \underline{K}_1; \qquad \underline{K}_1 = \underline{K}/K \tag{17a}$$

$$\underline{\mathbf{a}}_{|}(\underline{\mathbf{k}}) = \underline{K}_2 x \underline{\mathbf{a}}_k; \quad \underline{\mathbf{a}}_k = \underline{\mathbf{k}}/k \tag{17b}$$

With the formula for the far field [6]:

$$\underset{r\to\infty}{\underline{\mathbf{E}}(\underline{\mathbf{r}})} \approx -j.2\pi k\cos\theta.\underline{\mathbf{t}}(\underline{\mathbf{K}}).\frac{e^{+jkr}}{r}; \quad k\cos\theta \in R \tag{18}$$

and equation (15), the receiving far-field pattern is found to be:

$$\underset{\substack{r\to\infty \\ receive}}{\underline{\mathbf{E}}(\underline{\mathbf{r}})} \approx -j.\frac{2\pi k^2\eta_0}{\gamma\eta}.\cos\theta.\underline{\mathbf{r}}(-\underline{\mathbf{K}}).\frac{e^{+jkr}}{r}; \quad \eta = (\epsilon/\mu)^{1/2} \tag{19}$$

with $\underline{\mathbf{r}}(-\underline{\mathbf{K}})$ according to equation (16b) and:

$$\underline{\mathbf{K}} = k\sin\theta\cos\varphi.\underline{\mathbf{a}}_x + k\sin\theta\sin\varphi.\underline{\mathbf{a}}_y \tag{20}$$

4 CONCLUSION

For the planar near-field measurement situation in which the Antenna Under Test is acting as a receiving antenna, an identical transmission equation holds true as in the 'usual' situation, in which the Antenna Under Test is acting as a transmitting antenna. In both planar near-field measurement configurations, the characteristics of the Antenna Under Test can be found if the probe is completely characterized.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 POSITIONS)

IN THIS REPORT THE TRANSMISSION EQUATION FOR A PLANAR NEAR-FIELD MEASUREMENT CONFIGURATION IS DERIVED FOR THE SITUATION IN WHICH THE ANTENNA UNDER TEST IS OPERATED AS A RECEIVING ANTENNA. (USUALLY THE ANTENNA UNDER TEST IS OPERATED AS A TRANSMITTING ANTENNA).
THIS TRANSMISSION EQUATION HAS THE SAME FORM AS THAT DERIVED FOR THE SITUATION IN WHICH THE ANTENNA UNDER TEST IS ACTING AS TRANSMITTING ANTENNA. WITH THIS NEW DERIVED AND WITH THE EXISTING TRANSMISSION EQUATION, IT IS POSSIBLE TO CHARACTERIZE NON-RECIPROCAL ANTENNAS, PROVIDED THAT THE USED PROBE IS COMPLETELY CHARACTERIZED.

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